Fuzzy logic flowers in Japan

Born in the United States in the 1960s, the fuzzy logic approach is now catching on for many control and other applications

Fuzzy logic in Japan is becoming a textbook example of how a theory translates into applications. The idea was first broached by Lotfi A. Zadeh, a professor at the University of California at Berkeley, in a 1965 paper on fuzzy sets. Today Japanese manufacturers use fuzzy logic in everything from cameras to industrial process control. At times they even choose fuzzy logic controllers over conventional types, because the fuzzy kind are easier to design and so cheaper to produce.

Zadeh was struck by the fact that people can base decisions on imprecise, nonnumerical information. In 1965, he was implicitly advancing the thesis that this was one reason why people were better at control than machines. Surely, he argued, electromechanical controllers would respond better to imprecise input if their behavior were modeled on spontaneous human reasoning.

In his 1973 landmark paper in the *IEEE Transactions on Systems, Man and Cybernetics*, Zadeh introduced the concept of a linguistic variable, or one whose values are words, and not numbers. Thus, the linguistic variable "size" might have the values "large," "not very large," "small," and so on. In combination with the notion of a fuzzy IF-THEN rule—for example, "if pressure is very high, then volume is very low"—the concept paved the way for applying the theory to real tasks.

> A fuzzy controller handles adjustments the way a person thinks: it can set temperature low, medium or high

One application was fuzzy logic control.

Daniel G. Schwartz Florida State University
George J. Klir
State University of New York at Binghamton

In a seminal 1975 paper, Ebrahim H. Mamdani and S. Assilian of Queen Mary College, London, demonstrated that a very simple controller based on fuzzy logic could regulate a model steam engine. About the same time the first significant industrial application—F. L. Smidth Corp.'s cement kiln—came on line in Denmark.

By now these efforts have begun to blossom, primarily in Japan, in a variety of commercial and industrial applications. In 1991, Japan captured nearly 80 percent of the world market in fuzzy logic, along with estimated revenues of nearly US $150 million, gains that could approach $350 million in 1992, according to a recent report by Market Intelligence Research Corp., Mountain View, Calif. Furthermore, as of July 1991, 18 projects concerning fuzzy logic research and development were being funded by Japan's equivalent of the National Science Foundation in the United States, the Science and Technology Association, with substantial increases planned for the future.

FUZZY CONTROL. In a conventional proportional, integral, and differential (PID) controller, what is modeled is the system or process being controlled, whereas in a fuzzy logic controller, the focus is the human operator's behavior. In the first case, the system is modeled analytically by a set of differential equations, and their solution tells the PID controller how to adjust the system's control parameters for each type of behavior required. In the fuzzy controller, these adjustments are handled by a fuzzy rule-based expert system, a logical model of the thinking processes a person might go through in the course of manipulating the system. This shift in focus from the process to the person involved changes the entire approach to automatic control problems.

The inference rules in the fuzzy expert system may take the form "if observed variable x is 'positive medium,' then change the control variable y by the amount 'negative medium.'" The model derives the designation "fuzzy" from its use of such terms as "positive medium," "positive large," and "no change," which in turn form a fuzzy subset of the associated measurement domain. For example, a range of temperature measurements may be represented by the fuzzy subset "very low," "low," "medium," "high," and "very high," each of which is described by a membership function [Fig. 1]. As such, the system being controlled is formally viewed as a fuzzy system. This is why, by and large, fuzzy controllers are simpler than classical PID controllers—they tolerate a certain imprecision in dealing with the problem of control.

Each inference rule actually represents a collection of several rules, structured according to what Zadeh called a "compositional rule of inference." For example, take a rule that says that if the error of a controlled variable and the error's rate of change are "positive small," then the controlling variable should be set to "negative medium" [Fig. 2]]; this rule might also implicitly represent the rule that says that a "positive large" error and rate of change call for a "negative large" change in control.

The choice of a nonfuzzy (crisp) setting of the controlling variable, given one or more such fuzzy conclusions, is determined by a

Defining terms

Centroid calculation: (for determining the output of a fuzzy inference system) the computation of the center of gravity of a union of areas bound by membership functions and input signal axes.

Defuzzification: a procedure to find the best crisp (numerical) representation of a given fuzzy set.

Fuzzy control system: one based on fuzzy IF-THEN rules for logic and utilizing fuzzy sets for inputs and outputs.

Fuzzy inference system: a collection of fuzzy IF-THEN rules.

Fuzzy logic: logic that uses linguistic hedges ("very," "more or less," "extremely," and so on), fuzzy predicates ("large," "very large," "weak," "medium," and so on), and fuzzy quantifiers ("many," "almost all," "few," and so on).

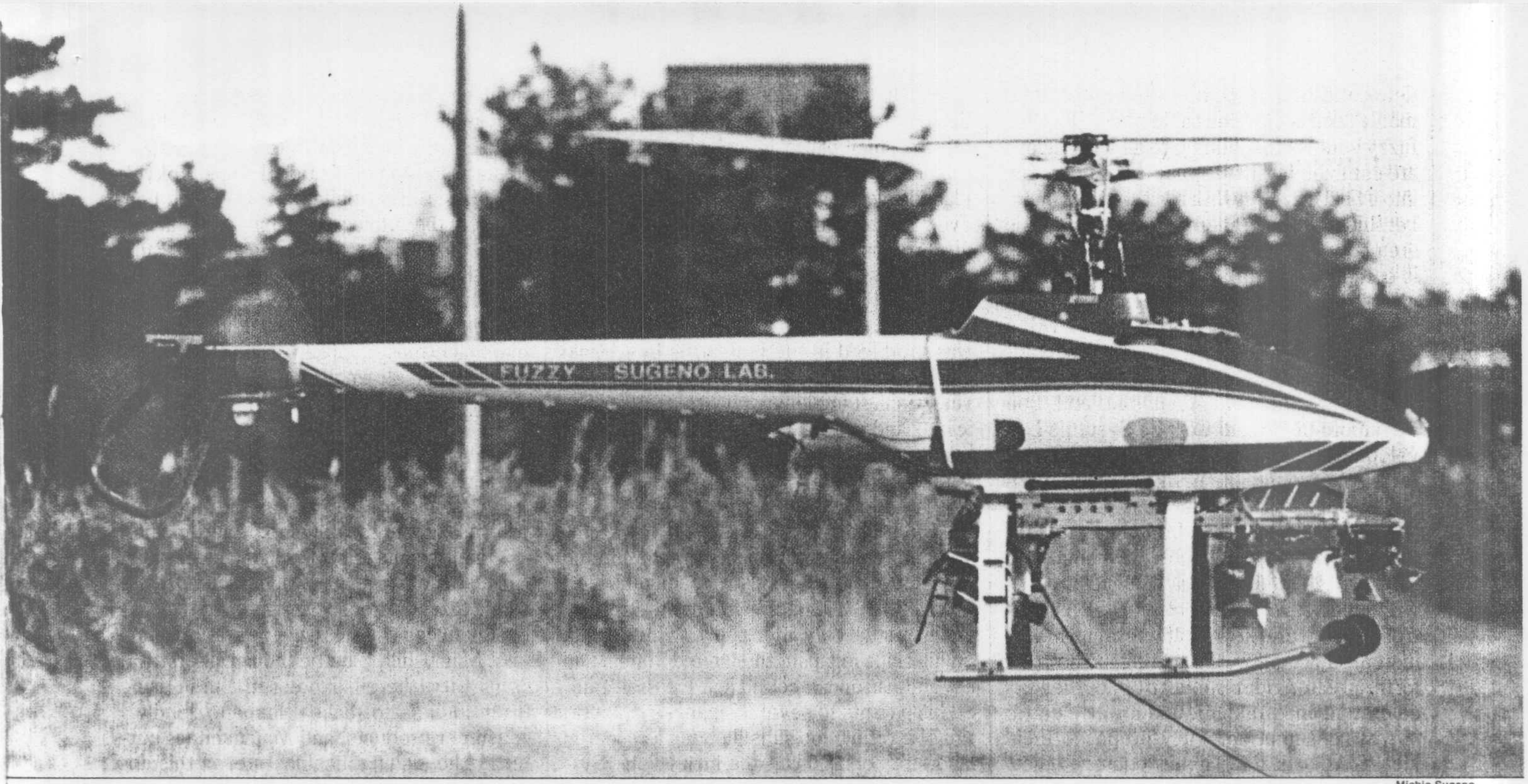
Fuzzy set: any set that allows its members to have different grades of membership, each expressed by a number in the interval [0,1].

Fuzzy system: a system whose variables range over states that are fuzzy sets.

Membership function: for a fuzzy set, the mapping that associates each member with its grade of membership.

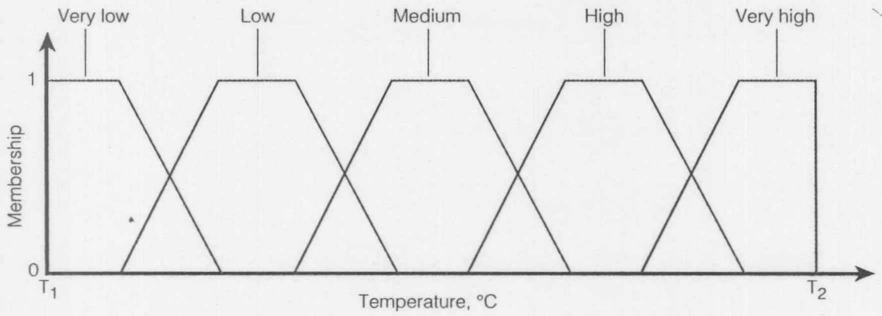
Neural network: a collection of independent processing nodes that communicate with one another in a manner roughly analogous to neurons in the human brain.

0018-9235/92/$3.00©1992 IEEE

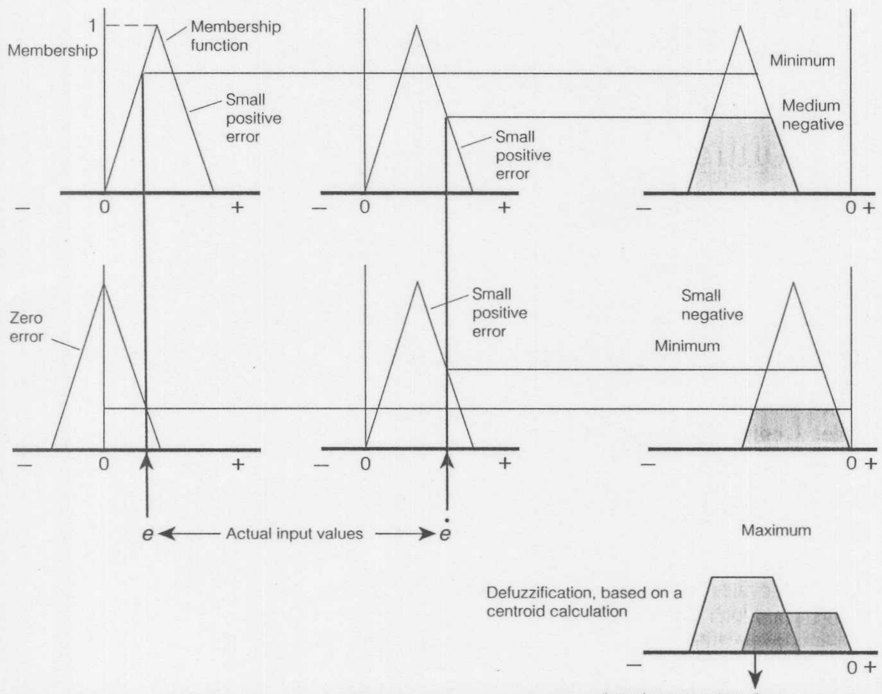


Michio Sugeno

A pilotless voice-controlled helicopter with a rotor 1 meter in diameter developed by Michio Sugeno at the Tokyo Institute of Technology responds to simple voice commands like "hover," "forward," and "up," with each of these functions being fully automated by fuzzy logic control.



[1] Five fuzzy states of a variable, say, temperature T *within a range* (T_1, T_2)*, are elements of a particular fuzzy set. Each state is described by an appropriate word—"low," "medium," and so on. Membership grade functions—curves relating the words to temperature values—have trapezoidal shapes here, as in most current industrial applications, though other shapes are possible.*



[2] The compositional rule of fuzzy inference is illustrated here by two hypothetical inference rules involving three variables: e*, error of a controlled variable;* ė*, rate of change in the error; and* c*, a controlling variable. The first rule is "If* e *is small positive and* ė *is small positive, then* c *is medium negative." The second rule is "If* e *is zero and* ė *is small positive, then* c *is small negative." Usually more rules are needed to achieve effective control [Fig. 3]. Defuzzification follows, here by the centroid method—calculation of the center of gravity of the shaded area—the abscissa of which yields the actual control output value. Other defuzzification schemes (not shown) are also used.*

defuzzification procedure. The most commonly used is the centroid method. Here the fuzzy sets corresponding to all conclusions are combined by a fuzzy set union operation into a final fuzzy set with its associated membership function. Then the centroid of the area bounded by this membership function is computed, and its abscissa taken as the crisp controlling value [Fig. 2].

SOFT LANDING. Credit for the next level of theoretical development and the first commercial implementation of these ideas in Japan goes to Seiji Yasunobu and Soji Miyamoto of Hitachi Corp.'s Systems Development Laboratory in Kawasaki. Fuzzy logic control made its market debut on the new Sendai railway, where it governs all aspects of accelerating, braking, and stopping. Through simulations, Yasunobu and Miyamoto had shown that their controller was superior to the conventional PID controller in several key parameters, including increased accuracy in stopping at the platform, greater rider comfort (smoother acceleration and braking), and lower electric power consumption. They proposed their ideas to Hitachi in 1983, they published their simulation results in 1985, and the Sendai Metro used their control when it opened in 1987. The Sendai project has been so successful that the city of Tokyo has recently decided to apply the same methods to a subway now under construction.

BALANCING ACT. A second event in 1987 combined with the Sendai railway opening to evoke a surge of interest in fuzzy control. At the Second Congress of the International Fuzzy Systems Association (IFSA-87), held in Tokyo, Takeshi Yamakawa demonstrated his inverted pendulum experiment. In this classic control problem, a pole is attached to a vehicle by a hinge such that from an upright position it can fall only to the right or left. The aim is to monitor the pole's angular position and speed and move the vehicle left or right accordingly, so as to keep the pole upright. The shorter and/or lighter the pole, the harder the balancing act.

Whereas Yasunobu and Miyamoto's controller for the Sendai train was implemented in software on a conventional digital computer, Yamakawa designed his own chips: a fuzzy rule chip, which implemented Zadeh's compositional rule of inference, and a defuzzifier chip, which implemented the centroid calculation.

The chips were analog and could run in parallel. The elementary operations employed in the compositional rule of inference, and also utilized in defuzzification, are the arithmetic max and min, which can run much faster on an analog device. The parallelism allowed multiple rules to be fired simultaneously, each on its own chip.

The controller presented at IFSA-87 used seven rule chips and one defuzzifier chip [Fig. 3], and it produced balancing responses nearly 100 times shorter than those of a conventional PID controller.

Yamakawa has since gone further and demonstrated nonlinear control with his system. A small platform was attached to the top of the inverted pendulum, and on it was placed a wine glass containing a liquid, or even a live white mouse. The controller nicely compensated for the turbulence of the liquid as well as the totally erratic movements of the mouse.

As for the world's very first fuzzy chip, it was produced in the mid-1970s by Masaki Togai, president of Togai Infralogic Inc., Irvine, Calif. It implemented just the arithmetic max and min operations often used in calculating fuzzy sets. Togai is now very active in the production of fuzzy-based electronics. In addition, Wei Xu, president of Aptronix Inc., San Jose, Calif., has recently developed chips and boards implementing assorted fuzzy inferencing techniques.

CORPORATE INVOLVEMENT. Yamakawa reported his results only after applying for patents on his chips in Japan, the United States, and several European countries. He then traded his patents to several Japanese corporations in return for subsidies for a research laboratory of his own—the Fuzzy Logic Systems Institute in Iizuka, with space for around 40 full-time researchers.

A major contributor to the institute is Omron Corp., Kyoto, which expects about 30 percent of its business (which totals 350 billion yen, or US $2.5 billion, in sales per year) to be fuzzy-related by 1995. This large electronics producer was the first Japanese company to ever obtain a patent for a fuzzy logic controller in the United States, and as of July 1991, claimed over 700 patents worldwide for fuzzy logic devices either acquired, pending, or in application. In addition to very large-scale ICs (VLSI) and boards, these cover a camera that can follow moving objects and a robot sensitive enough to lift cakes of bean curd.

> The hard part of designing a fuzzy controller is its tuning—teaching it to represent human reasoning

Omron currently employs more than 50 engineers on fuzzy systems R&D, with applications covering tracking problems, tuning, human factors, interpolation, and classification, including handwriting recognition, to mention just a few. As of July 1991, Omron had plans to develop some 40 fuzzy logic devices for use in automobiles, for example, antilock brakes, automatic transmission systems, impact warning and monitoring, windshield washers, light dimmers, and so on.

Plenty of fuzzy consumer products are available in Japan, and a few are now being sold in the United States and Europe. Almost all use fuzzy logic controllers implemented in software on conventional chips. Tokyo's Canon Inc. has applied a fuzzy logic controller in the autofocus mechanism of its new 8-mm movie camera. The Matsushita/Panasonic Palmcorder uses fuzzy logic for image stabilization in a video camera for consumers—the first of its kind. Several major Japanese appliance manufacturers now have their own fuzzy washing machine, which automatically adjusts the washing cycle for load size, type and amount of dirt, and fabric type. Fuzzy control also shows up in vacuum cleaners, air-conditioners, electric fans, and hot plates, plus the automatic transmission in the new Lexus automobile.

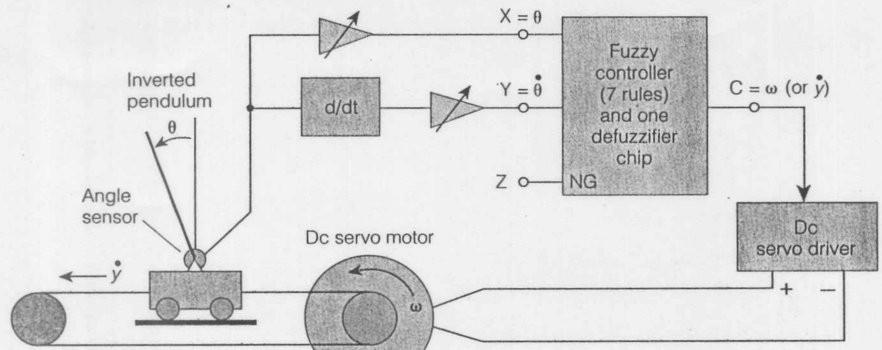
Other manufacturers include Tokyo's OKI Electric Industry Co., which has been marketing fuzzy inference hardware, and recently announced a new fuzzy inference chip.

At Matsushita Electric Industrial Co., Kadoma City, the oft-expressed aim in using fuzzy logic is to make "human friendly" consumer products, and Matsushita is currently the leading manufacturer in this domain. Other producers of fuzzy consumer and/or industrial products include Fuji Photo Film (controlling the flow of powders), Hitachi (control of banks of elevators), Mitsubishi Electric (air conditioning), Nissan Motor (automatic transmission), and Toshiba (ventilation system for expressway tunnels). And this list is far from exhaustive.

RECENT DEVELOPMENTS. An intriguing project is the voice-controlled helicopter being developed by Michio Sugeno at the Tokyo Institute of Technology. Here the objective is to develop a helicopter that obeys voice commands like "hover," "forward," "left," "up," and "land." The control of each axis uses essentially the same fuzzy techniques as ensured vertical stability in Yamakawa'a inverted pendulum.

Hovering is a formidable stability problem—would-be helicopter pilots typically train for weeks before managing to do it manually. Hence automating this operation is in itself an impressive achievement. Sugeno has accomplished all functions for a model with a 1-meter rotor [photo, p. 33], and is working on a 3-meter model. He reported on his current progress at the 1992 IEEE First International Fuzzy Systems Conference in San Diego, Calif., March 8-12.

While the principles of fuzzy control have been understood for some time, no application until recently employed more than a few inference rules. Usually the hardest part of designing fuzzy controller is selecting which fuzzy sets best represent the controlled and controlling variables, namely, the "tuning" of the controller. Most controllers are sensitive to the shapes [for example, the trapezoids in Fig. 1] of these membership functions, and as the number of rules multiplies, trial-and-error tuning



[3] In Takeshi Yamakawa's inverted pendulum stabilized by a fuzzy controller, θ is angle of pendulum from vertical, ω is angular velocity of the servo motor, ẏ is horizontal velocity of the vehicle. An input for a third (unused) variable is set to NG *(negation) [top]. A table of θ shows seven rules, for example, "if θ is* PM *(positive medium) and θ̇ is* ZR *(about zero), then ẏ is* PM*." Other states used are NL, NM, PS, and PL ("negative low and medium," "positive small and large," respectively). The experiment shows there is no need for rules that correspond to the blanks in the table.*

θ̇ \ θ	NL	NM	NS	ZR	PS	PM	PL
PL							
PM							
PS			ZR		PS		
ZR		NM		ZR		PM	
NS			NS		ZR		
NM							
NL							

Source: *Fuzzy Sets and Systems*, Vol. 32, 1989, pp. 177–78 (courtesy of Elsevier Science Publishers and Takeshi Yamakawa)

methods become less and less feasible.

A recent breakthrough here calls on a neural network, which with the aid of back propagation learns the needed membership functions from a set of training examples. (A neural network interconnects processing nodes in imitation of the neurons in the human brain; the back propagation type carries out supervised learning by feeding output failures to match a desired target pattern back to its input as information to its individual nodes.) Hideyuki Tagaki and Isao Hayashi, researchers with Matsushita's Central Research Laboratory, Osaka, first reported these results at the 1988 International Conference on Fuzzy Logic and Neural Networks, Iizuka, Fukuoka.

Subsequently, Akira Maeda and others of Hitachi's Systems Development Laboratory, Tokyo, have based a tuning system on this idea and applied it in the development of a controller designed previously by trial and error. In just one month they accomplished a tuning task that had formerly taken six. Similar work has been undertaken by, among others, Toshiro Terano of Hosei University, and Masao Mukaidono of Meiji University, both in Tokyo. Nowadays advertisements in Japan for "neuro-fuzzy" products are common, and the two technologies seem likely to continue to evolve in tandem.

Fuzzy control for robots is being pursued by Kaoru Hirota at Hosei University and Shigeki Ishikawa at IBM Japan, in Tokyo. One of Hirota's more dramatic efforts directs a robot to throw darts at an object falling through an array of pegs, as in a pinball machine, so that it scores a hit on just about every try. The robot is a general-purpose, programmable device, and is now being marketed by Mitsubishi. Ishikawa has produced an autonomous robot that uses fuzzy control to avoid stationary and moving obstacles, particularly for seeing their sizes and shapes. Among some more exotic applications are robots for making Japanese flower arrangements, for Chinese character calligraphy, and for inspection of plant seedlings.

OTHER RESEARCH. While the greatest achievements have been in fuzzy logic control, work is in progress in other domains. Tokyo's Hitachi Corp. markets a fuzzy expert system shell, ES/Kernel, which has now sold over 2000 copies. (A shell is a computer program that embodies various knowledge representation and inferencing techniques, and serves as a framework within which to develop specific expert systems.) The Ministry of International Trade and Industry's six-year project, the Laboratory for International Fuzzy Engineering Research (LIFE), continues to pursue fuzzy logic applications in: decision support; robotics, including natural language and image understanding; and fuzzy computing, including fuzzy associative memories. At his Fuzzy Logic Systems Institute, Yamakawa recently unveiled his VLSI "fuzzy neuron" in an experiment in handwritten-character recognition. A fuzzy neuron is analogous to the neuron of hardware implementations of neural networks, except that it takes fuzzy sets as inputs and yields a fuzzy set as output.

At the Hiroshima Institute of Technology, Kazuho Tamano has had preliminary success with an optical fuzzy inference device. Here light is passed through translucent plates on which are inscribed the membership functions of fuzzy sets representing a rule's premises, and the amount of light coming out is measured to derive the rule's conclusion.

Also of interest is Hirota's design for a fuzzy flip-flop circuit, which includes the binary flip-flop as a special case. There has been discussion about initiating a project to develop a fuzzy computer based on Hirota's circuit designs. The machine would embody both fuzzy (multilevel) and classical (binary) information processing in the same machine.

TO PROBE FURTHER. An IEEE video conference entitled "Fuzzy Logic: Applications and Perspectives," featuring Masaki Togai, Lotfi Zadeh, and Piero Bonissone, aired April 25, 1991 (the 41st IEEE video conference, available on tape). The 1992 IEEE First International Fuzzy Systems Conference took place in March in San Diego, Calif. For a conference proceeding (IEEE Pub. No. 92 CH3073-4), contact IEEE Service Center, 445 Hoes Lane, Box 1331, Piscataway, N.J., 8855-1331; 908-981-0060.

A rich source of information on various aspects of fuzzy set theory and fuzzy logic is *Fuzzy Sets and Applications: Selected Papers by L.A. Zadeh*, ed. R.R. Yager et al. (John Wiley, New York, 1987). A simple and self-contained introduction to fuzzy set theory with a strong coverage of measures of uncertainty and information is *Fuzzy Sets, Uncertainty, and Information* by G.J. Klir and T.A. Folger (Prentice-Hall, Englewood Cliffs, N.J., 1988). An excellent overview of fuzzy control is to be found in the paper "Fuzzy Logic in Control Systems" by C.C. Lee (*IEEE Trans. on Systems, Man and Cybernetics*, SMC, Vol. 20, No. 2, 1990, pp. 404–35).

ACKNOWLEDGMENTS. The article is based on the authors' trips to Japan last year, which were supported by separate grants from the U.S. Office of Naval Research, along with a two-month appointment of Dan Schwartz as visiting researcher at Kansai University, Osaka. We wish to thank our various Japanese hosts for their warm and generous hospitality.

ABOUT THE AUTHORS. Daniel G. Schwartz is an associate professor of computer science at Florida State University, Tallahassee, concentrating on researching the formal aspects of fuzzy logic.

George J. Klir (SM) is chairman and distinguished professor of systems science at the Thomas J. Watson School of Engineering and Applied Science, State University of New York at Binghamton. He is a former president of the North American Fuzzy Information Processing Society (Nafips), president elect of the International Fuzzy Systems Association (IFSA), as well as a former president of the International Federation for Systems Research (IFR). ◆